Field Crops Research 143 (2013) 4–17

Contents lists available at SciVerse ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Yield gap analysis with local to global relevance—A review

Martin K. van Ittersum[a,*], Kenneth G. Cassman[b], Patricio Grassini[b], Joost Wolf[a], Pablo Tittonell[c], Zvi Hochman[d]

[a] *Plant Production Systems group, Wageningen University, P.O. Box 430, 6700 AK Wageningen, The Netherlands*
[b] *University of Nebraska-Lincoln, P.O. Box 830915, Lincoln, NE 68583-0915, USA*
[c] *Farming Systems Ecology group, Wageningen University, P.O. Box 563, 6700 AN Wageningen, The Netherlands*
[d] *CSIRO Ecosystem Sciences/Sustainable Agriculture Flagship, EcoSciences Precinct, 41 Boggo Road, Dutton Park, QLD 4102, Australia*

ARTICLE INFO

Article history:
Received 27 April 2012
Received in revised form
13 September 2012
Accepted 16 September 2012

Keywords:
Food security
Yield potential
Water-limited yield potential
Yield gaps
Boundary function
Crop simulation models
Cropping system

ABSTRACT

Yields of crops must increase substantially over the coming decades to keep pace with global food demand driven by population and income growth. Ultimately global food production capacity will be limited by the amount of land and water resources available and suitable for crop production, and by biophysical limits on crop growth. Quantifying food production capacity on every hectare of current farmland in a consistent and transparent manner is needed to inform decisions on policy, research, development and investment that aim to affect future crop yield and land use, and to inform on-ground action by local farmers through their knowledge networks. Crop production capacity can be evaluated by estimating potential yield and water-limited yield levels as benchmarks for crop production under, respectively, irrigated and rainfed conditions. The differences between these theoretical yield levels and actual farmers' yields define the yield gaps, and precise spatially explicit knowledge about these yield gaps is essential to guide sustainable intensification of agriculture. This paper reviews methods to estimate yield gaps, with a focus on the local-to-global relevance of outcomes. Empirical methods estimate yield potential from 90 to 95th percentiles of farmers' yields, maximum yields from experiment stations, growers' yield contests or boundary functions; these are compared with crop simulation of potential or water-limited yields. Comparisons utilize detailed data sets from western Kenya, Nebraska (USA) and Victoria (Australia). We then review global studies, often performed by non-agricultural scientists, aimed at yield and sometimes yield gap assessment and compare several studies in terms of outcomes for regions in Nebraska, Kenya and The Netherlands. Based on our review we recommend key components for a yield gap assessment that can be applied at local to global scales. Given lack of data for some regions, the protocol recommends use of a tiered approach with preferred use of crop growth simulation models applied to relatively homogenous climate zones for which measured weather data are available. Within such zones simulations are performed for the dominant soils and cropping systems considering current spatial distribution of crops. Need for accurate agronomic and current yield data together with calibrated and validated crop models and upscaling methods is emphasized. The bottom-up application of this global protocol allows verification of estimated yield gaps with on-farm data and experiments.

1. Introduction

Whereas seven years ago there was relatively little concern for meeting projected food demand through improvements in crop productivity, today there is increasing awareness that "business as usual" will not allow food production to keep pace with demand—a situation that may result in dramatic rises in food prices, poverty, and hunger (FAO, 2003, 2006; Royal Society of London, 2009; Koning and van Ittersum, 2009; Godfray et al., 2010). Indeed, until recently, the most widely used computational equilibrium models that evaluate global food supply and demand predicted that grain prices would remain constant or decrease in coming decades (Rosegrant et al., 1995, 2002; Colby et al., 1997; Cranfield et al., 1998; Rosegrant and Cline, 2003).

Three things are responsible for this remarkable turnaround in prognosis for global food security: (1) economic development rates in the world's most populous countries have consistently exceeded projections by a wide margin; (2) large increases in demand for energy, grain, and livestock products in these countries due to a rapid rise in purchasing power; and (3) global slowing of crop yield rates of grain (Cassman et al., 2003, 2010; Steinfeld et al., 2006; Royal Society of London, 2009; Brisson et al., 2010; Fischer and Edmeades, 2010). It is now clear that during the next several decades, as human population rises towards a climax at 9 + billion,

---

* Corresponding author. Tel.: +31 317482382; fax: +31 317484892.
E-mail address: martin.vanittersum@wur.nl (M.K. van Ittersum).

0378-4290/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.fcr.2012.09.009

every hectare of existing crop land will need to produce yields that are substantially greater than current yield levels. However, some regions have much greater potential than others to support higher yields in a sustainable manner, due to their favourable climate, soil quality, and in some cases, access to irrigation. In some of these favourable regions current average farm yields are low. Hence, a large exploitable gap exists between current yields and what is theoretically achievable under ideal management.

Given the need for sustainable intensification, identifying regions with greatest potential to increase food supply is critical for four reasons. First, yield gap analysis provides the foundation for identifying the most important crop, and soil and management factors limiting current farm yields and improved practices to close the gap. Second, to enable effective prioritization of research, development, and interventions. Third is to evaluate impact of climate change and other future scenarios that influence land and natural resource use. And fourth, results from such analysis are key inputs to economic models that assess food security and land use at different spatial scales. Computable general and partial equilibrium models typically rely on historical yield trends with some kind of extrapolation into the future. However, the agronomic basis of such projections and associated resource requirements can be much improved through rigorous yield gap analyses.

For all these reasons, a geospatially explicit assessment of exploitable gaps is required for the major food crops worldwide with local, agronomic relevance and with public access. And while more detailed information about yield gaps is necessary, it is not sufficient to fully inform research prioritization and investment strategies. Analyses of markets, policies, infrastructure and institutional factors are also needed. Without yield gap assessment coupled with appropriate socio-economic analysis of constraints to improved productivity, policy makers and researchers will find it difficult to accurately assess future food security and land use change. This in turn may lead to policy development and research prioritization that are not well-informed, especially in developing regions such as Sub-Saharan Africa and South Asia where current information is sparse.

The usefulness and rigor of yield gap analyses is demonstrated by various examples. Already in the 1960s, when average farmer yields were below 5 Mg ha^{-1} in the Netherlands, it was computed that wheat yields could exceed 10 Mg ha^{-1} (De Wit, 1959; Alberda, 1962). While few believed this could be true at that time, since 1993 average farmers' yields in important wheat growing areas in the Netherlands have regularly exceeded 9 or even 10 Mg ha^{-1} (Centraal Bureau voor de Statistiek). In Australia, the early work of French and Schultz (1984) estimated water-limited yields and showed that yields were limited by factors other than water, despite farmers' perception that water was the single most limiting factor. Recognition of these other limiting factors led to identification of improved management practices such that yield gaps are now smaller (Hochman et al., 2012a,b). Yield gap analyses for Southeast Asia helped explain yield trends in irrigated rice and revealed that nitrogen management had to be improved to increase yields (Kropff et al., 1993). In Nebraska, recent yield gap analysis of irrigated maize identified the recent plateauing of yields in farmers' fields to be associated with a yield level about 85% of the yield potential ceiling (Grassini et al., 2011a), which is similar to yield levels at which other crops have plateaued (Cassman et al., 2003, 2010).

This review aims at comparing and assessing different methods of yield gap analysis across spatial scales from the field, to sub-national and national scales, to identify key components of yield gap analysis that ensure adequate transparency, accuracy, and reproducibility. In this paper we begin with definitions and a conceptual framework for agronomically relevant yield gap assessment, and then evaluate the strengths and limitations of previously published local and global yield gaps. Based on this analysis, we identify the key components and associated uncertainties of a global protocol for yield gap analysis to produce locally relevant outcomes that can be aggregated to regional or national estimates.

2. Concepts

Yield potential (Yp), also called potential yield, is the yield of a crop cultivar when grown with water and nutrients non-limiting and biotic stress effectively controlled (Evans, 1993; Van Ittersum and Rabbinge, 1997). When grown under conditions that can achieve Yp, crop growth rate is determined only by solar radiation, temperature, atmospheric CO_2 and genetic traits that govern length of growing period (called cultivar or hybrid maturity) and light interception by the crop canopy (e.g., canopy architecture). Potential yield is location specific because of the climate, but in theory not dependent on soil properties assuming that the required water and nutrients can be added through management (which, of course, is not practical or cost-effective in cases where major soil constraints, such as salinity or physical barriers to root proliferation, are difficult to overcome). Thus, in areas without major soil constraints, Yp is the most relevant benchmark for irrigated systems or systems in humid climates with adequate water supply to avoid water deficits. For rainfed crops, water-limited yield (Yw), equivalent to water-limited potential yield, is the most relevant benchmark. For partially (supplementary) irrigated crops, both Yp and Yw may serve as useful benchmark. Definition of Yw is similar to Yp, but crop growth is also limited by water supply, and hence influenced by soil type (water holding capacity and rooting depth) and field topography (runoff).

Both Yp and Yw are calculated for optimum or recommended sowing dates, planting density and cultivar (which determines growing period to maturity). Sowing dates and cultivar maturity are specified to fit within the dominant cropping system because the cropping system "context" is critically important in dictating feasible growth duration, particularly in tropical and semi-tropical environments where two or even three crops are produced each year on the same piece of land. Farmers attempt to maximize production and/or profit for the entire cropping system rather than the yield or profit of an individual crop. Likewise, where machinery and labour are limiting or costly, achieving optimal sowing dates may not be feasible for most farms. We therefore argue it is also relevant to calculate Yp and Yw for current average or median planting dates in addition to optimal dates.

Average yield (Ya) is defined as the yield actually achieved in a farmer's field. To represent variation in time and space in a defined geographical region, it is defined as the average yield (in space and time) achieved by farmers in the region under the most widely used management practices (sowing date, cultivar maturity, and plant density, nutrient management and crop protection). The number of years utilized for estimating Ya must be a compromise between variability in yields and the necessity to avoid confounding effects of temporal yield trends due to technological or climate change (see Section 4).

The yield gap (Yg) is the difference between Yp (irrigated crops), or Yw (rainfed crops) and actual yields (Ya). Water resources to support rainfed and irrigated agriculture also are under pressure, making water productivity (WP—the efficiency with which water is converted to food) another critical benchmark of food production and resource use efficiency (Bessembinder et al., 2005; Passioura, 2006; Grassini et al., 2011b). Water productivity is defined as the ratio between (grain) yield and seasonal water supply, which includes plant-available soil water at planting, in-season rainfall, and applied irrigation (irrigated crops) minus the residual plant-available water in the root zone at maturity.